AN EXTENDED ABSTRACT FOR AIAA CONFERENCE

Light-Weight Injector Technology for Cryogenic Mars Ascent Engines

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Introduction

Preliminary mission studies for human exploration of Mars[1] have been performed at Marshall Space Flight Center (MSFC). These studies indicate that for chemical rockets only a cryogenic propulsion system would provide high enough performance to be considered for a Mars ascent vehicle. Although the mission is possible with Earth-supplied propellants for this vehicle, utilization of in-situ propellants is highly attractive. This option would significantly reduce the overall mass of launch vehicles. Consequently, the cost of the mission would be greatly reduced because the number and size of the Earth launch vehicle(s) needed for the mission decrease. NASA/Johnson Space Center has initiated several concept studies[2] of in-situ propellant production plants. Liquid oxygen (LOX) is the primary candidate for an in-situ oxidizer. In-situ fuel candidates include methane (CH_4), ethylene (C_2H_4), and methanol (CH_3OH).

MSFC initiated a technology development program for a cryogenic propulsion system for the Mars human exploration mission in 1998. One part of this technology program is the effort described here: an evaluation of propellant injection concepts for a LOX/liquid methane Mars Ascent Engine (MAE) with an emphasis on light-weight, high efficiency, reliability, and thermal compatibility. In addition to the main objective, hot-fire tests of the subject injectors will be used to test other key technologies including light-weight combustion chamber materials and advanced ignition concepts.

This state-of-the-art technology will then be applied to the development of a cryogenic propulsion system that will meet the requirements of the planned Mars sample return (MSR) mission.[3] The current baseline propulsion system for the MSR mission uses a storable propellant combination [monomethyl hydrazine/mixed oxides of nitrogen-25 (MMH/MON-25)].[4] However, a mission option that incorporates in-situ propellant production and utilization for the ascent stage is being carefully considered as a subscale precursor to a future human mission to Mars.

MAE Injector Design

1) Baseline Engine

A propulsion system study[5] conducted at MSFC has shown that a pressure-fed system is suitable for a cryogenic ascent stage for the MSR mission. This system was selected based on several factors including weight minimization, packaging efficiency, and

operational simplicity. While a regulated pressurization system is planned for the first-stage of the Mars Ascent Vehicle, a blow-down pressurization system is baselined for the second-stage.

Table 1 summarizes key MAE operating conditions derived from the MSFC system study. The injector technology program uses the data shown in the third column as baseline design conditions. The last column of Table 1 shows a range of operating conditions for the blow-down situation. The planned injector test program will be conducted at chamber pressures (P_c) and mixture ratios (MR) varying from 250 to 550 psia and 1.5 to 4.0, respectively. Both the LOX ($P_{critical}$=731 psia) and liquid methane ($P_{critical}$=668 psia) are in the subcritical pressure regime throughout the expected range of chamber pressures.

2) Injector Configurations

Jet impinging injectors have commonly been used in LOX/liquid hydrocarbon rocket engines. For small rocket engines, triplet and unlike-impinging configurations are widely employed. Typically they provide higher performance than other configurations such as like-on-like impingement and shower-head. In this study, a split-triplet (F-O-O-F) arrangement, which was introduced by Pavli,[6] has been selected as the baseline. This configuration, as shown in Figure 1, is similar to a conventional triplet (F-O-F) impinger; the only difference is an additional oxidizer orifice on the split-triplet for reducing the disparity between the fuel and oxidizer orifice sizes. This arrangement is suitable for the MAE since the baseline O/F mixture ratio is 3.

An unlike-doublet (F-O) was selected as an alternative configuration. At first glance, this configuration resembles the split-triplet, if two unlike-doublet elements are arranged on the injector face with a back-to-back position, (F-O) and (O-F). However, this unlike-doublet grouping may result in an oxygen-rich region between the two injection elements. To avoid this situation, the elements, as shown in Figure 2, are oriented on the injector face as (F-O) and (F-O).

Because the MAE is relatively small, full-size injectors (2.4-inches in diameter) have been designed and fabricated. Injectors were designed to achieve the objectives of light weight and high performance while ensuring thermal compatibility and combustion stability. In order to optimize the manifold system and assure a uniform mass distribution, the injection elements are equally distributed in the circumferential direction. For the split-triplet, only a single ring of injection elements fit into the injector. On the other hand, two rings of unlike impinging elements fit in the injector face. In all cases the outermost ring of orifices injects fuel in order to prevent an oxygen-rich environment near the chamber walls.

A total of ten versions of the two basic injector configurations were designed and fabricated. Variations in the impinging height, impinging angle, orifice size, and injection element arrangement, as shown in Table 2, are utilized in these injector face designs. For the unlike doublet injectors (F-O-F-O), an oxygen-rich condition may exist at the centerline region of the injector face. To minimize this condition, the fuel orifices on the inner element ring are canted at an angle in the radial direction (Figure 2). This

orientation permits fuel to penetrate into the core region to provide additional propellant mixing. Several cant angles, as listed in Table 2, will be examined.

3) Combustion Instability

A reduction in pressure drop (ΔP) across an injector face will result in a lower tank pressure requirement which in turn will reduce the overall propulsion system weight. The desire to reduce propulsion system weight must be balanced with the need to provide adequate injector ΔP to ensure combustion stability. For this study, $\Delta P/P_c$ ratios for both the fuel and oxidizer injector flowpaths will be varied from 9 to 14%. Lower ΔP values may violate the chug margin and cause combustion instabilities.

Injector orifices were sized primarily based on combustion stability considerations. To size fuel orifices, Hewitt's correlation(7) has been employed to scale injector configurations from Pavli's data.(6) Oxidizer orifice sizes were selected to be similar to the fuel orifices, while keeping their momentum ratio very close to the values at optimum mixing. In addition, several acoustic cavity tuning blocks have been designed to accommodate two quarter-wave acoustic cavity sizes, 0.5" and 1" in depth. These tuning blocks will be used to characterize the combustion stability behavior of the candidate injectors.

Test Hardware and Facility

1) Test Hardware

The test hardware includes the MSFC Modular Combustion Test Article (MCTA), and the injector hardware built specifically for this program. The MCTA , as shown in Figure 3, is a "workhorse" combustion chamber. It is composed of several modules, which are held together by four high-strength tie rods. The copper throat section contains drilled passages for counterflowing cooling water. The cylindrical portion of the 4-inch diameter chamber consists of several modules, including a window module and an igniter/instrumentation module. The window module provides optical access to the chamber for photographing the flowfield or for performing non-intrusive optical diagnostics. There are several ports in the igniter/instrumentation module, one of which is used for a conventional gaseous hydrogen/gaseous oxygen torch igniter system. Pressure transducers and thermocouples may be installed into other ports in this module. The length of the combustion chamber can be altered by inserting blank modules of various lengths.

The injector assembly consists of an annular injection ring, an acoustic cavity tuning block, and a main injector. Nitrogen will be introduced as a film coolant along the chamber wall through a series of small orifices in the annular injection ring. A space between the annular injection ring and the main injector will serve as an acoustic cavity to enhance combustion stability. Different cavity configurations can be tested by changing tuning blocks. The main injector will flow liquid methane and liquid oxygen into the combustion chamber. The injector face, which is made of copper, is brazed to a manifold that has several concentric channels to distribute the propellants.

2) Test Facility

Injector testing will be conducted at Test Stand 115 in MSFC's East Test Area. This open-air test position includes a digital control system, analog and digital data acquisition systems, and cameras for recording video and high-speed film. A semi-trailer is used to house lasers, computers, and other combustion diagnostics equipment. This trailer provides a controlled environment for the equipment in close proximity to the test article.

Propellants can be provided at a variety of conditions at Test Stand 115. For the MAE program, LOX is supplied from a 500 gallon run tank at pressures up to 3000 psi. Liquid methane is stored in a 2200 gallon vacuum-jacketed vessel. Two foam-insulated fuel run tanks are available: a 20 gallon, 3000 psi tank for short duration tests, and a 500 gallon, 3000 psi tank for longer duration tests.

High pressure gases are available on the test stand for purging and pressurization (helium and nitrogen) and for igniter propellants (oxygen and hydrogen). De-ionized water for cooling the MCTA throat section is supplied from a 500 gallon, 3000 psi tank.

Project Status

At this time, MCTA modifications and all injector hardware fabrication have been completed. Cold-flow tests on the first two injectors, a standard triplet and an unlike-doublet, are in progress. The purpose of these tests is to determine if the injector manifold distributes the flow as designed and to measure the propellant mixing characteristics of the injectors under cold-flow conditions. The cold-flow data along with future hot-fire test results will provide information for developing useful correlations between these two conditions.

Initial cold-flow test results, as depicted in Figure 4, show that injector discharge coefficients for the oxygen system are lower than the design goal. It is suspected that the down-comers connecting the injector inlet boss to the manifold channels (Figure 5) have a higher than expected flow resistance due to a high length/diameter ratio. This design is unique because the injector module was adapted to the existing MCTA design envelope. (Note: When an injector assembly is designed for a flight engine, its length will be significantly shorter than the current one, and the down-comer's cross section will be in the form of a slot rather than a circle.) The current plan is to test a single element of the existing injector module by plugging the remaining injector orifices. The source of flow resistance as well as the approximate discharge coefficients for the injector orifices can then be determined from these results.

The MCTA has been assembled for hardware checkout tests. Ongoing facility work includes re-activation of the liquid methane storage and supply system. At the present time, approximately 50% of the facility build-up has been accomplished.

Future Work

Prior to hot-fire testing, cold-flow tests will be conducted on each injector configuration. Water and silicone oil will be used as oxidizer and fuel simulants, respectively. The local mixture of fuel and oxidizer simulants will be collected by a patternator system at a given

distance downstream of the injector face. Propellant mixing characteristics of injectors under cold-flow conditions will be assessed.

For the hot-fire program, injectors will be tested over a range of operating conditions, (Table 1). Combustion efficiency and stability will be analyzed by measured parameters such as propellant flowrates, and low-frequency and high-frequency chamber pressure measurements. Thermocouples installed in the MCTA instrumentation module will record the wall temperature. Measurement of the local temperature on the injector face will be attempted through the use of an infrared video imaging technique. Presently, this imaging technique is being calibrated with a copper sample in a high temperature oven. It should be noted that, at this time, there is no plan to test all ten injectors. The results from the initial injector tests will determine which additional configurations will be tested.

In the next phase of the program, the most promising injector configuration will be selected for additional testing with the light-weight chamber materials and the advanced igniter concepts. A high-speed (5000 frames/sec) video camera will be used for analyzing the ignition process.

In parallel with these efforts, the Materials and Processes Laboratory at MSFC is investigating a copper-based advanced light-weight metal matrix composite (MMC). Preliminary studies show this MMC material to be a promising candidate for a light-weight injector assembly. The current plan is to continue evaluating this MMC for strength and thermal compatibility, and ultimately to use it for injector hardware fabrication. Additional hot-fire tests with an MMC injector will then be performed.

Acknowledgments

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Table 1: MAE Operating Conditions

Parameter	**Unit**	**Baseline**	**Range**
Chamber Pressure	Psia	250	100 - 550
Mixture Ratio		3	(N/A)
Thrust	Lbf	600	300 - 1000
Vacuum Specific Impulse	Second	346	(N/A)
Exit/Throat Area Ratio		100	(N/A)
Mass Flow Rate	Lbm/sec	1.86	0.86 - 2.87

Table 2: Injector Configurations

No.	Injector Type	Config.	Inj. Core No.	# Elem.	Orifice Dia. LOX (in)	Orifice Dia. CH4 (in)	Cant Angle (deg)	Imping. Height (in)	Outer Ring Imping. Angle (deg)	Inner Ring Imping. Angle (deg)
1	SPLIT TRIPLET	F-OO-F	1	24	0.042	0.03	(N/A)	0.35	30	30
2	UNLIKE DOUBLET	F-O-F-O	2	30	0.05	0.035	0	0.35	28.4	21.8
3	UNLIKE DOUBLET	F-O-F-O	2	30	0.05	0.035	19	0.35	28.4	21.8
4	UNLIKE DOUBLET	F-O-F-O	2	30	0.05	0.035	67	0.35	28.4	21.8
5	UNLIKE DOUBLET	F-O-O-F	1	32	0.05	0.035	0	0.35	29.8	22.3
6	UNLIKE DOUBLET	F-O-F-O	2	42	0.042	0.03	43	0.35	28.4	26.4
7	SPLIT TRIPLET	F-OO-F	1	24	0.042	0.028	(N/A)	0.25	34.8	34.8
8	UNLIKE DOUBLET	F-O-F-O	2	42	0.042	0.03	43	0.25	33	30.8
9	UNLIKE DOUBLET	F-O-F-O	2	36	0.046	0.032	43	0.4	26.6	24.63
10	SPLIT TRIPLET	F-OO-F	1	16	0.046	0.034	(N/A)	0.4	28.5	28.5

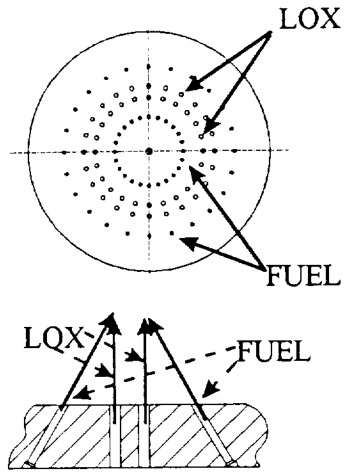

Figure 1: Split Triplet Injector (F-OO-F)
(a) Injector Face, (b) Injection Element

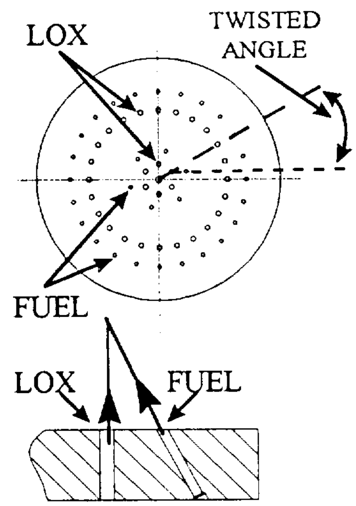

Figure 2: Unlike doublet Injector (F-O-F-O)
(a) Injector Face, (b) Injection Element

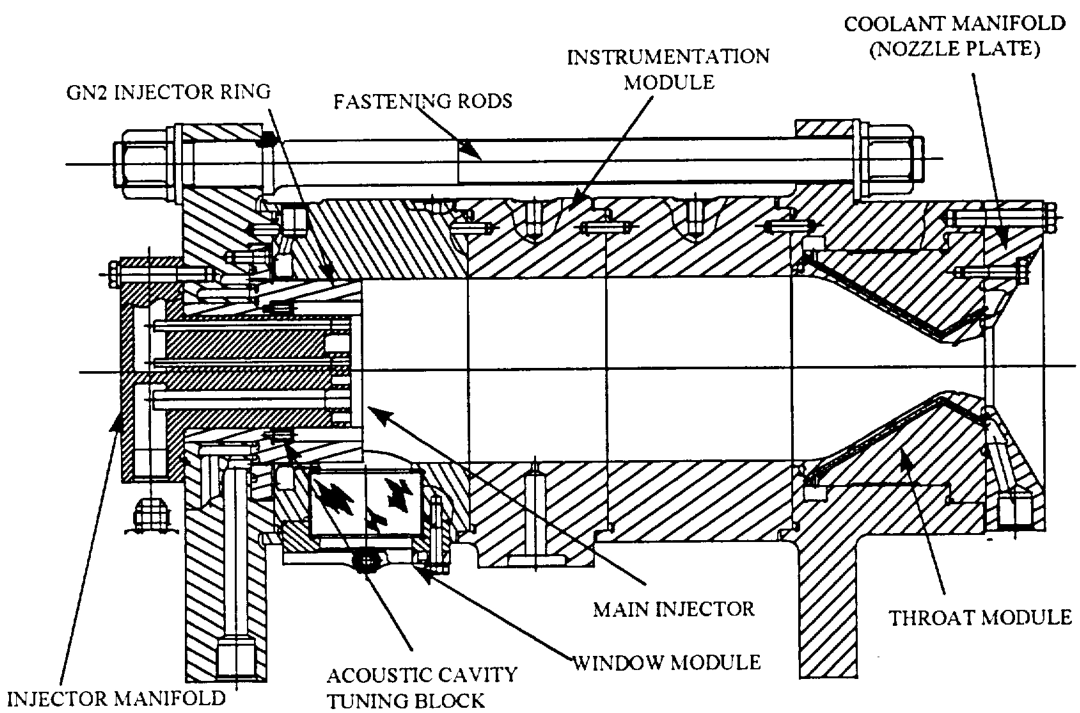

Figure 3: MCTA with an Injector Assembly

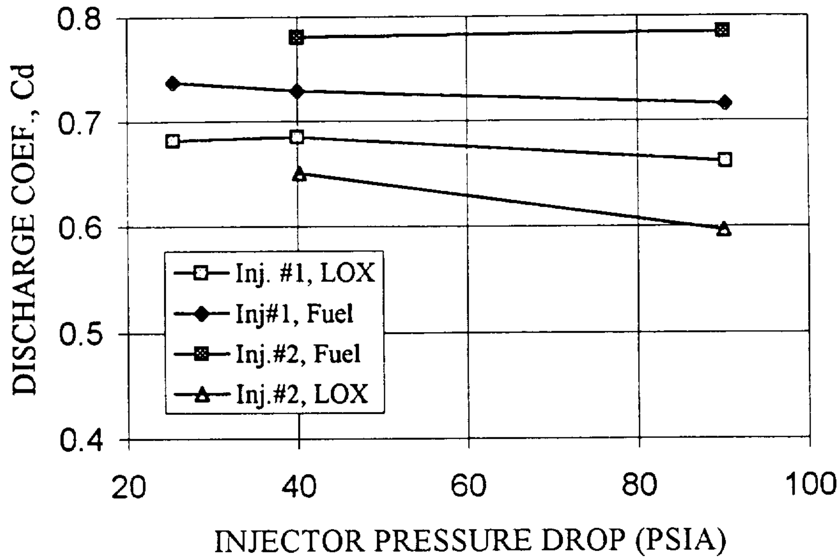

Figure 4: Injector Discharge Coefficients of Injector # 1 (Split-Triplet) and Injector # 2 (Unlike-Doublet)

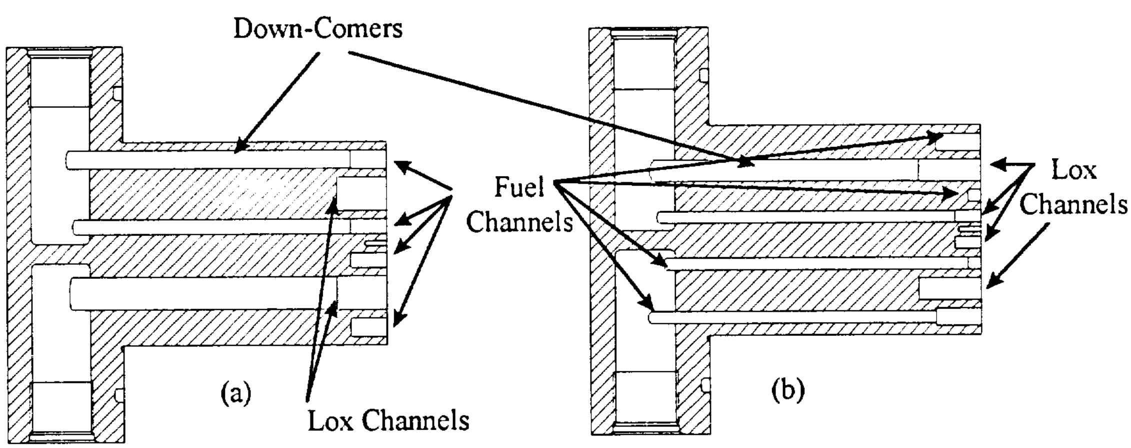

Figure 5: Injector Cores of Impinging Injectors, (a) Unlike-Doublet (F-O-F-O) (b) Split-Triplet (F-OO-F) and Unlike-Doublet (F-O-O-F)